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(54) **MICRO DEVICE WITH STABILIZATION POST**

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(52) **U.S. Cl.**

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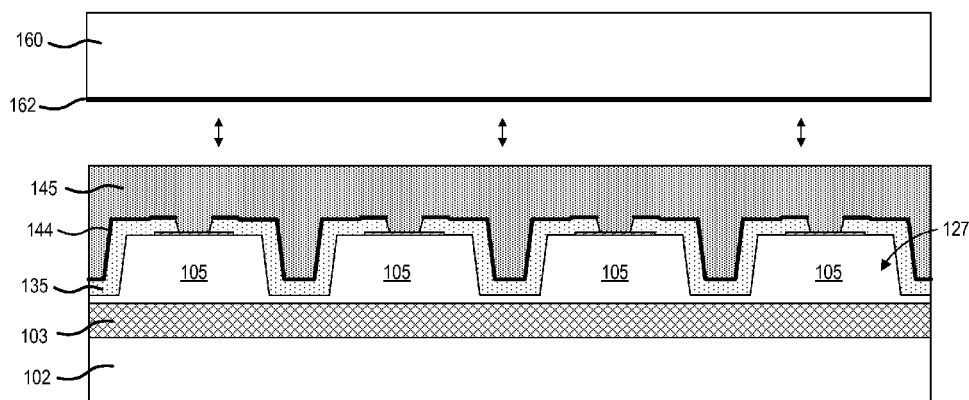
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(57)

ABSTRACT

A method and structure for stabilizing an array of micro devices is disclosed. A stabilization layer includes an array of stabilization cavities and array of stabilization posts. Each stabilization cavity includes sidewalls surrounding a stabilization post. The array of micro devices is on the array of stabilization posts. Each micro device in the array of micro devices includes a bottom surface that is wider than a corresponding stabilization post directly underneath the bottom surface.

10 Claims, 16 Drawing Sheets



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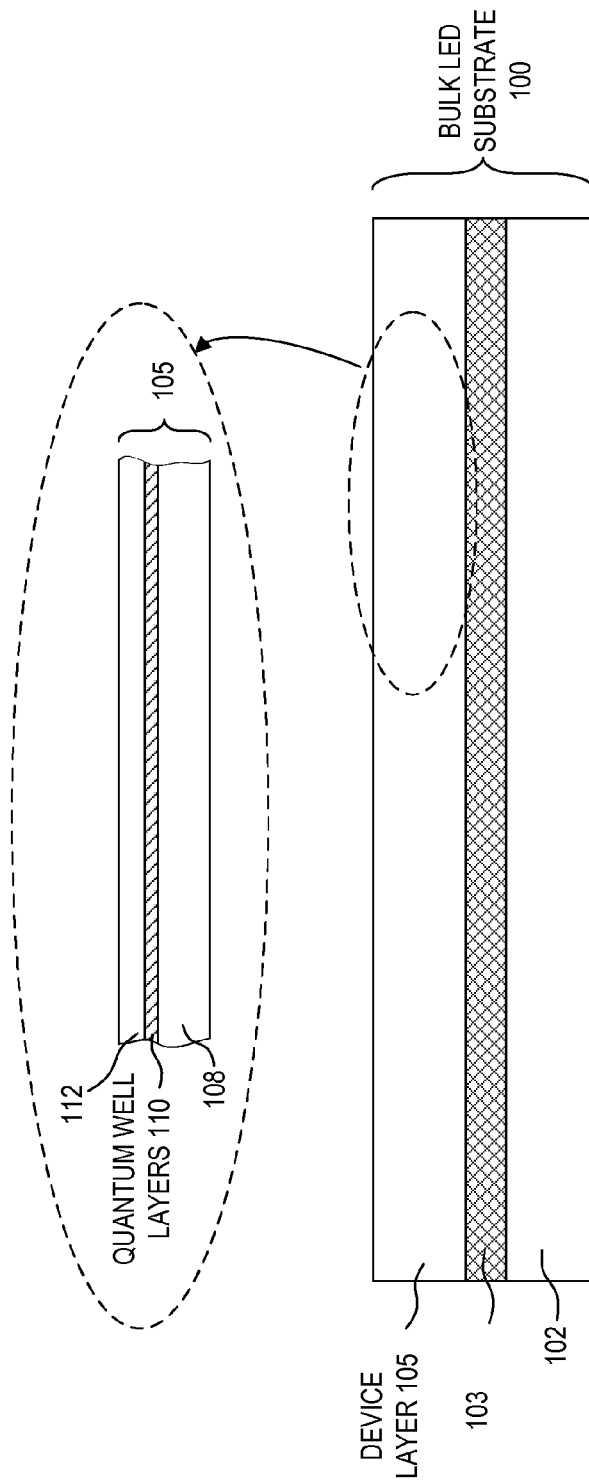


FIG. 1A

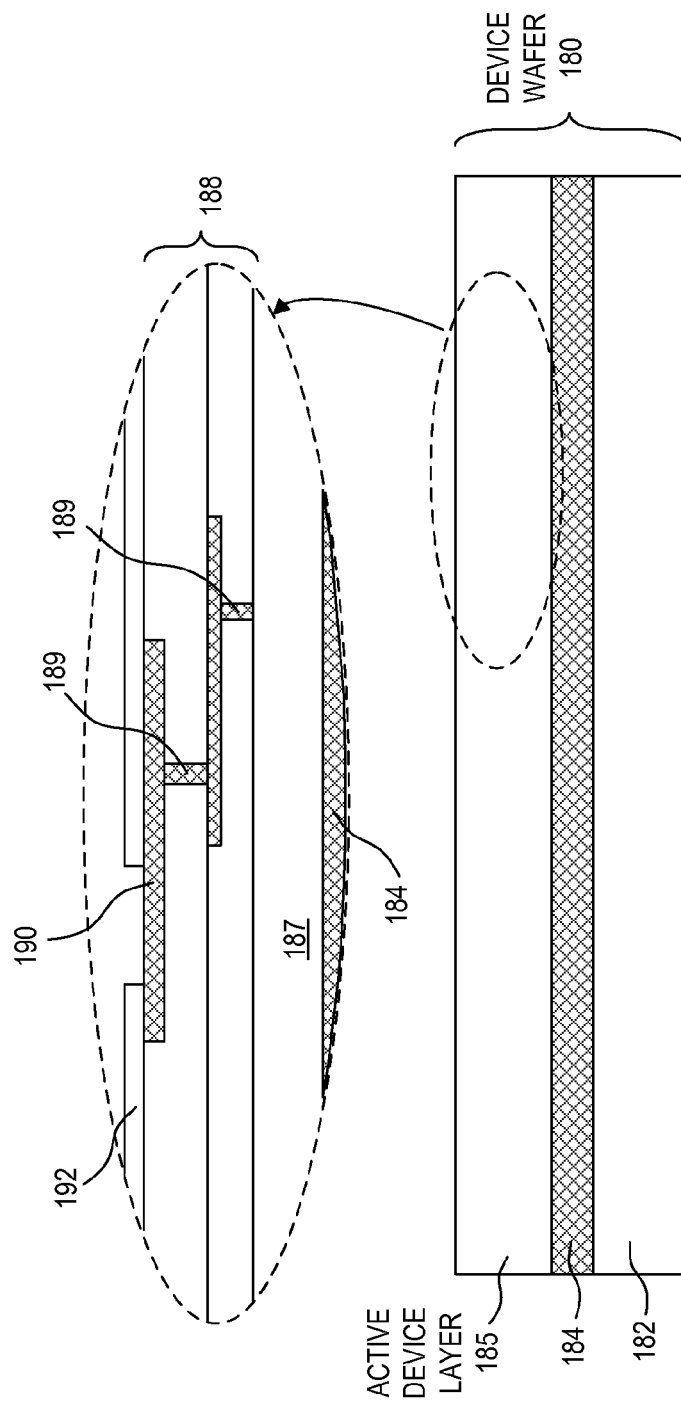


FIG. 1B

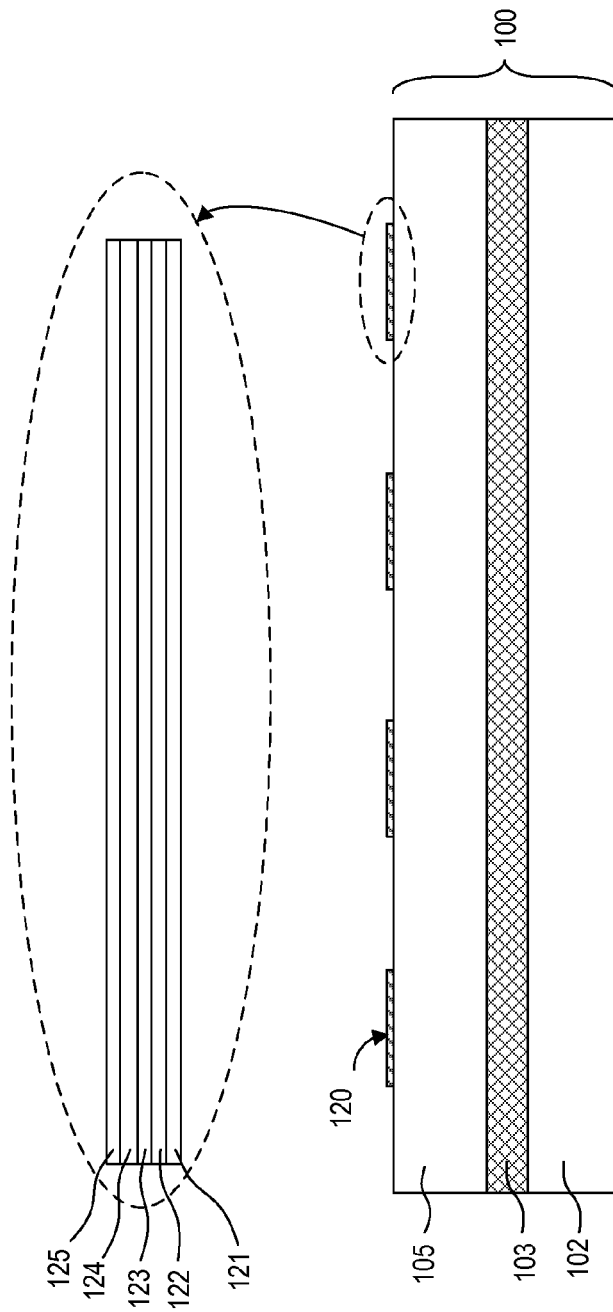


FIG. 2A

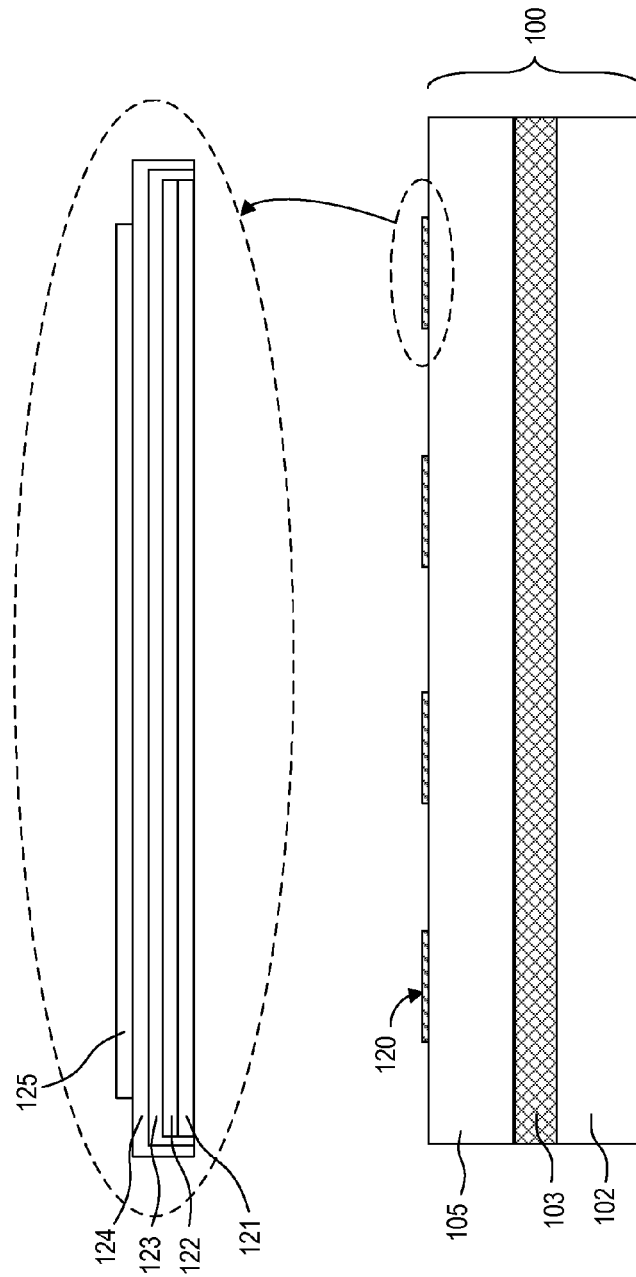


FIG. 2B

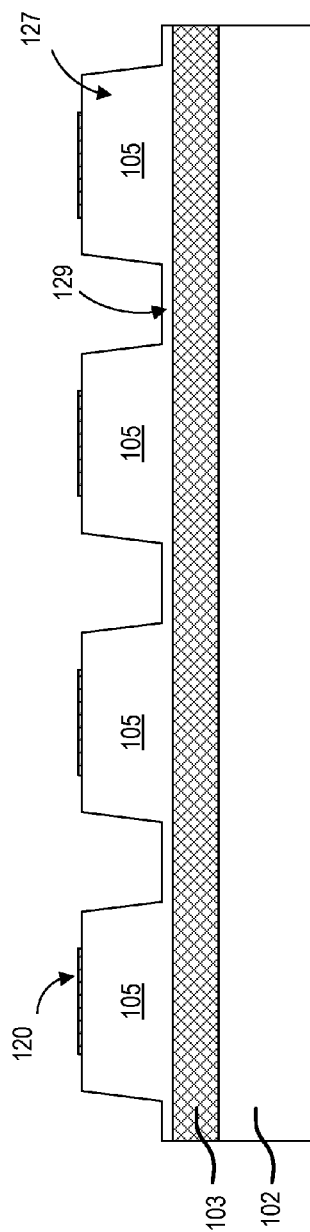


FIG. 3

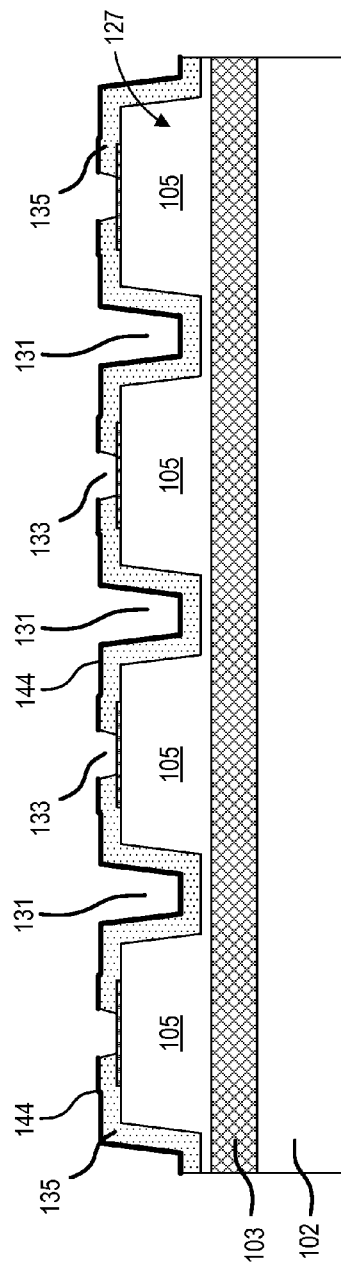


FIG. 4

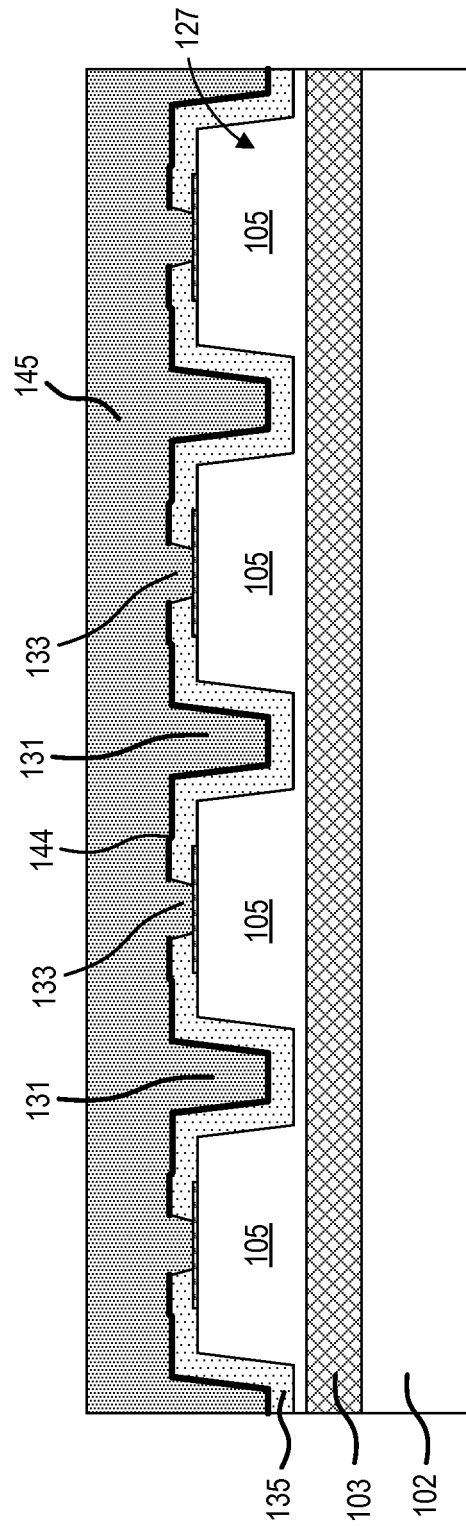


FIG. 5

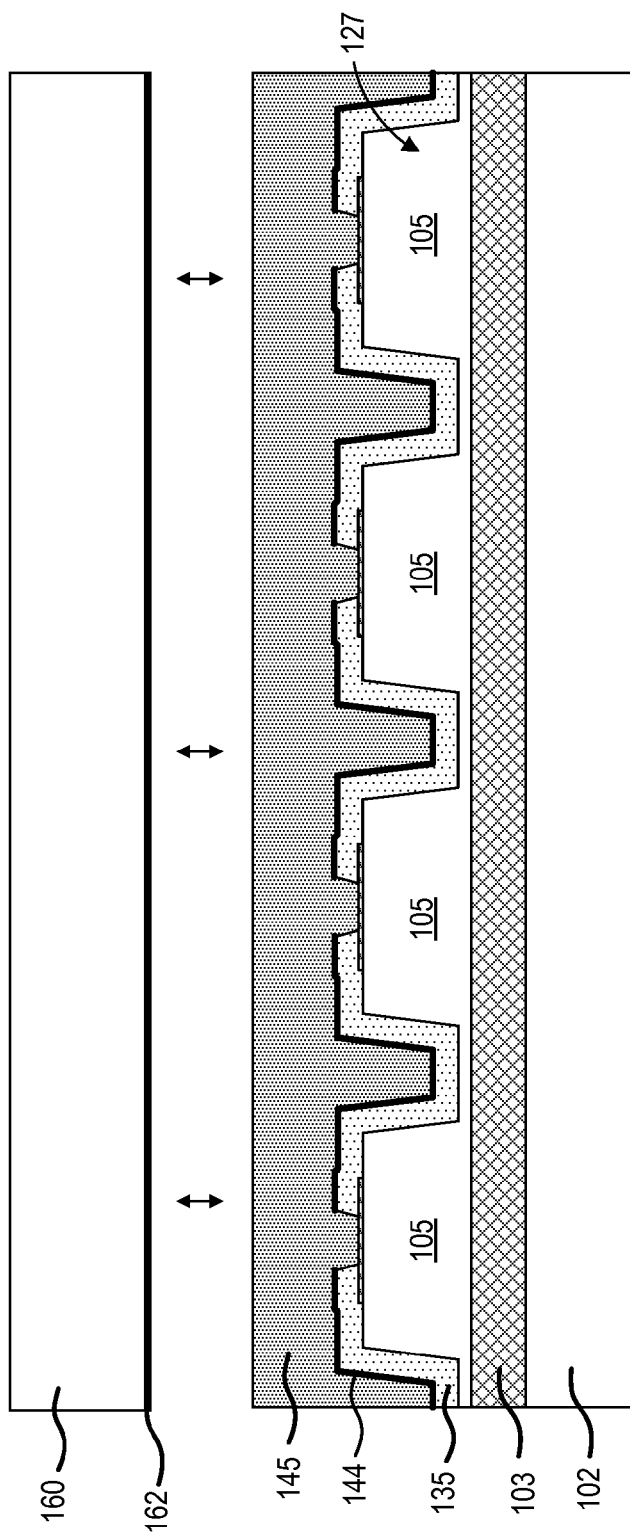


FIG. 6

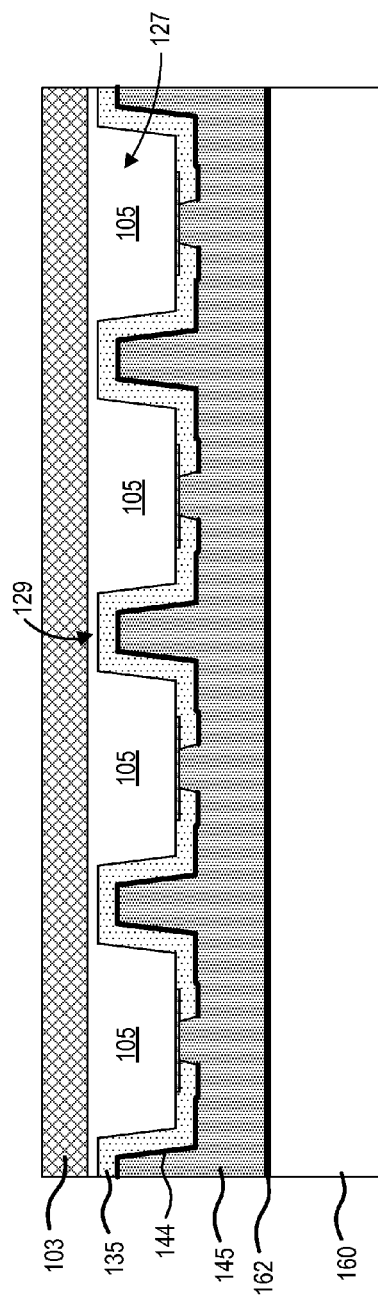


FIG. 7

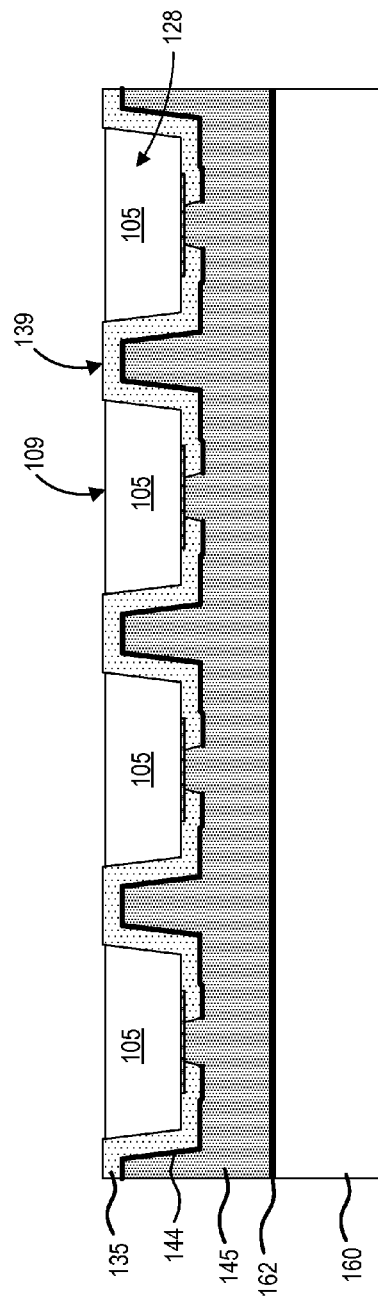


FIG. 8

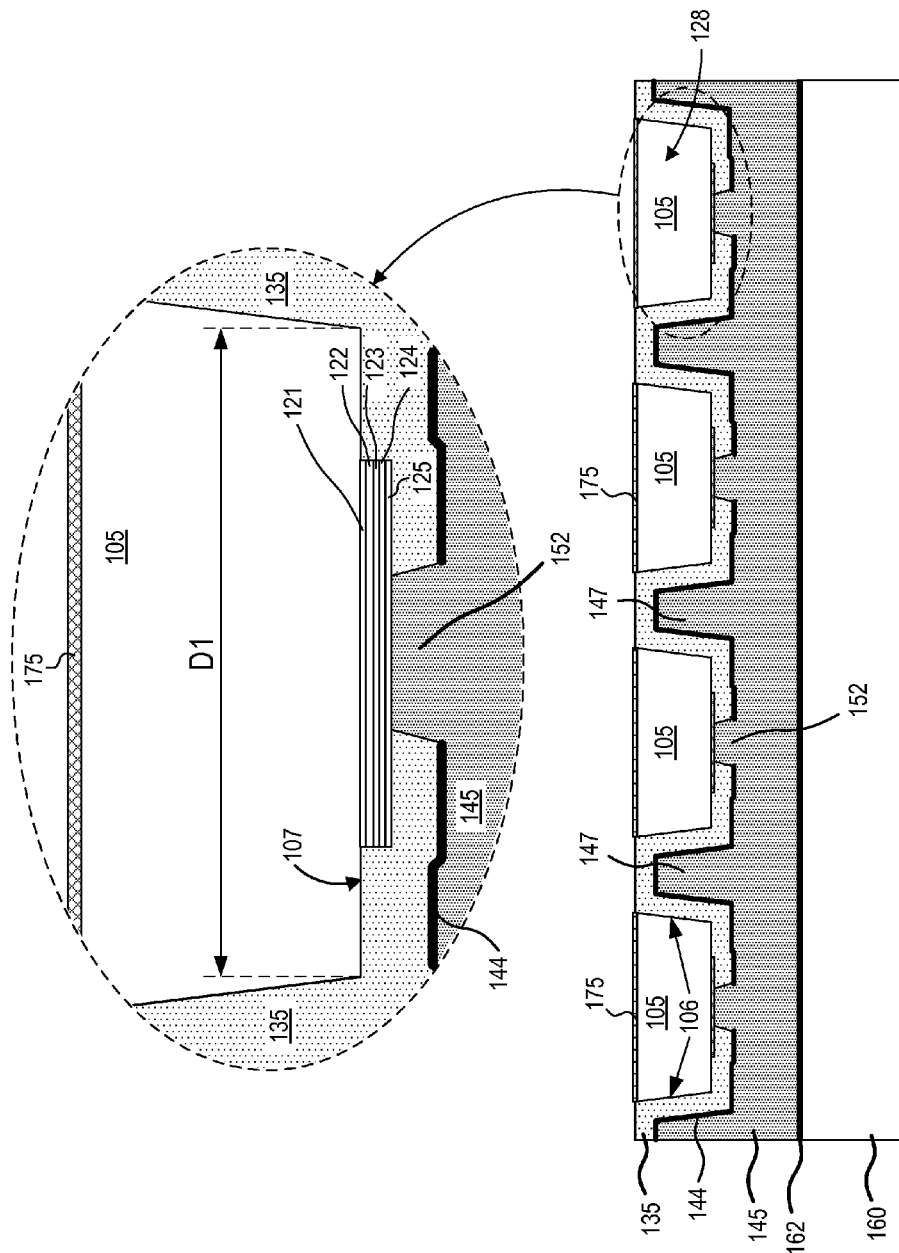


FIG. 9A

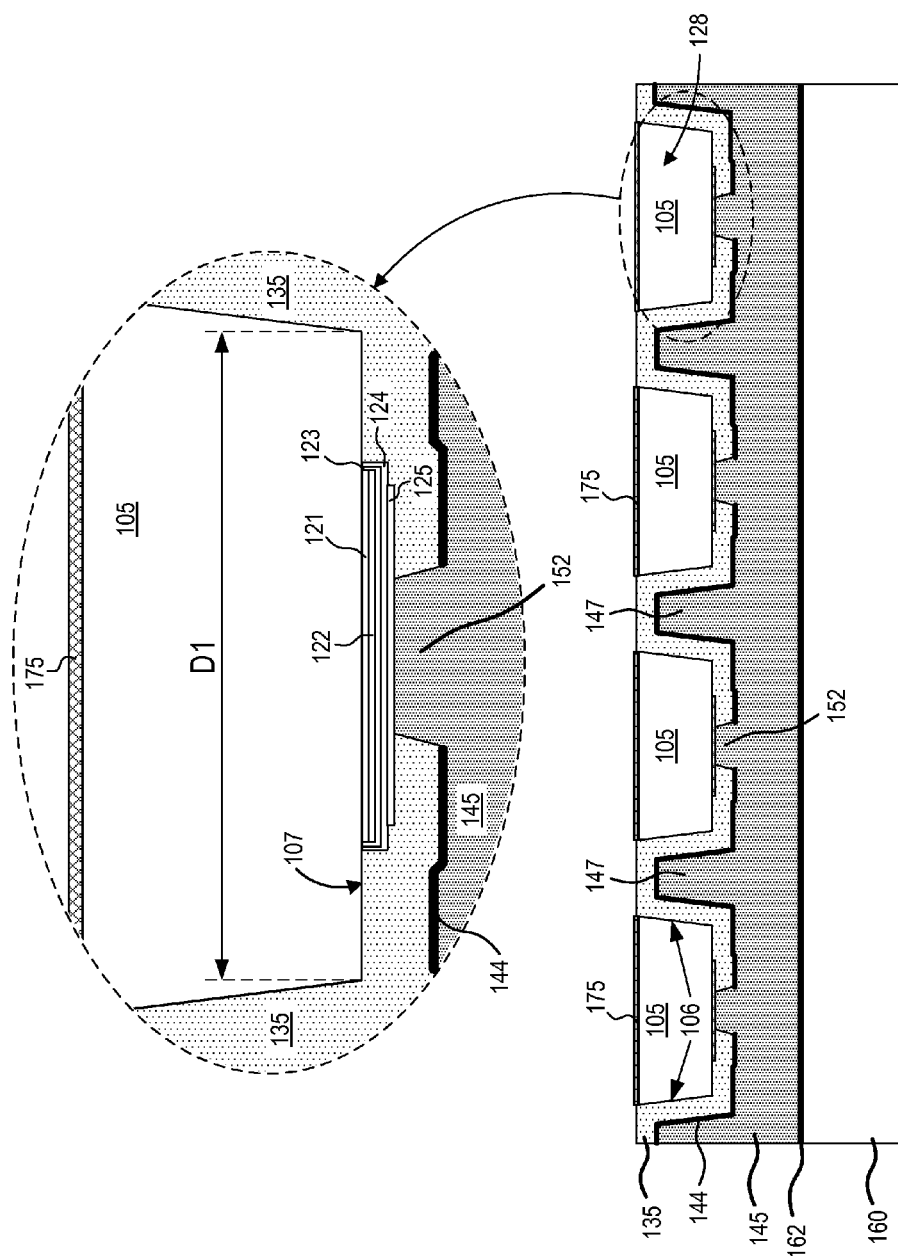


FIG. 9B

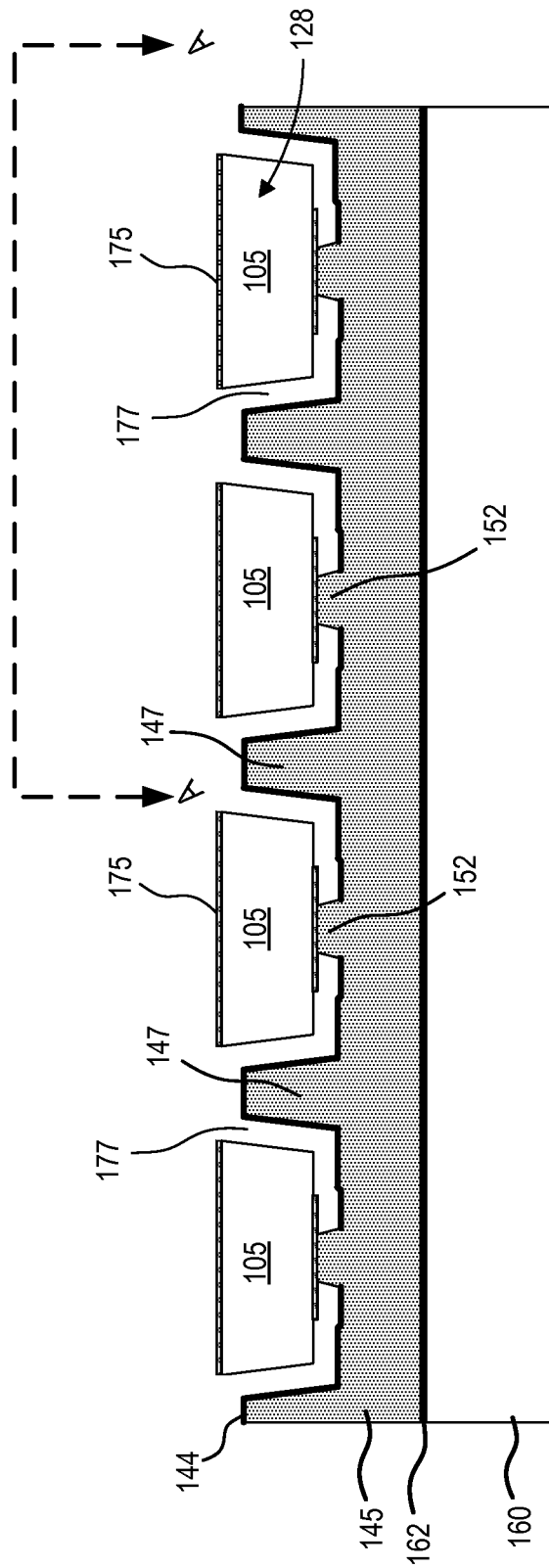


FIG. 10A

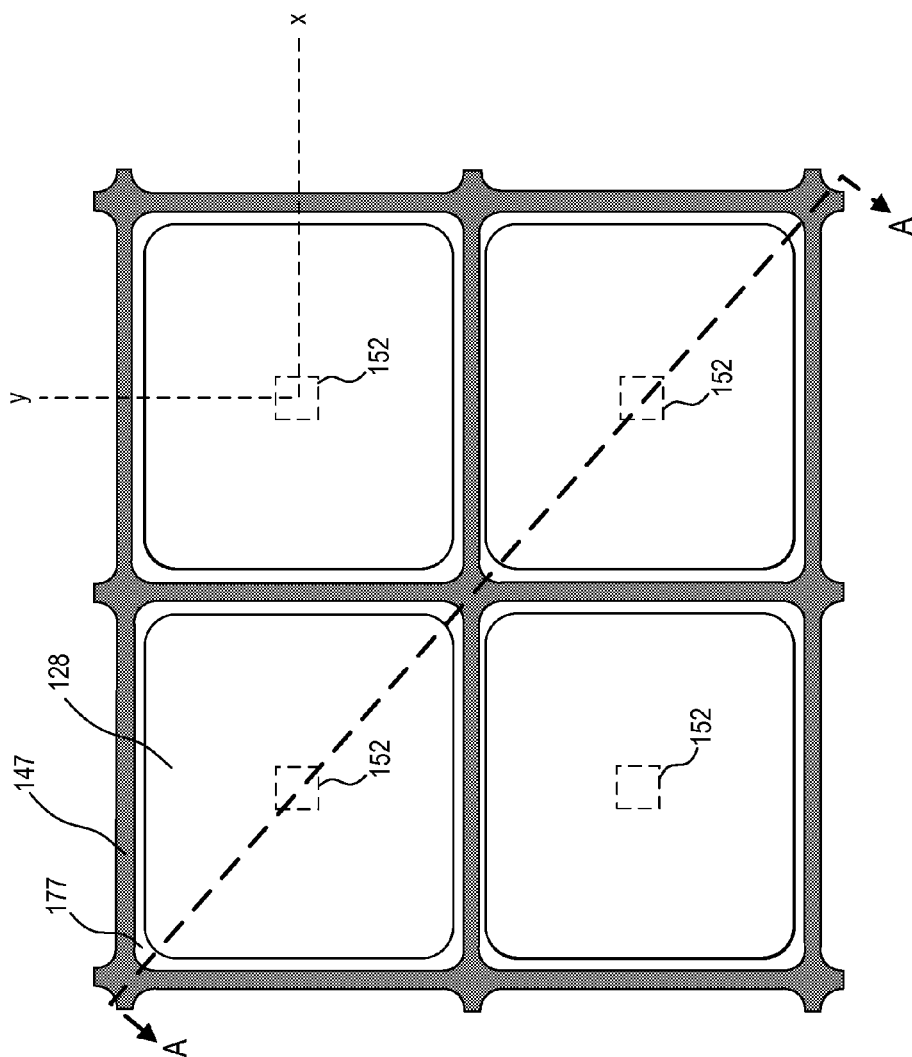


FIG. 10B

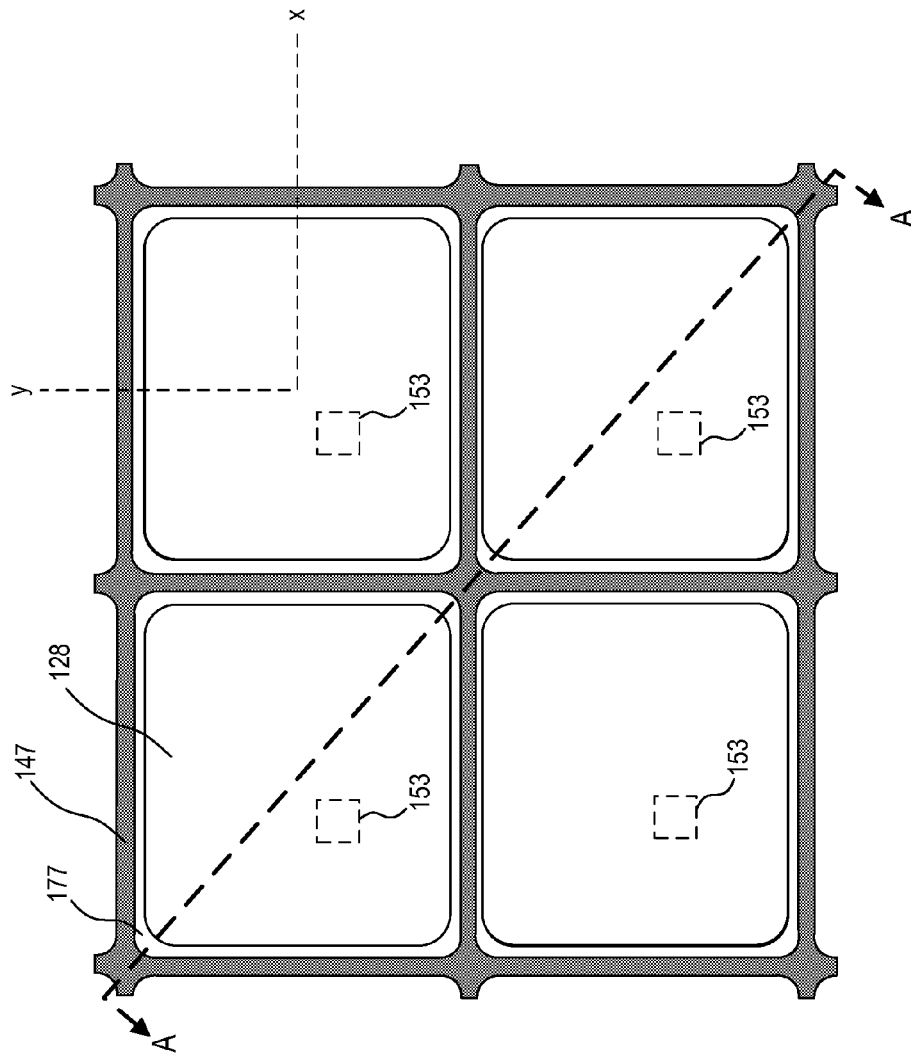


FIG. 10C

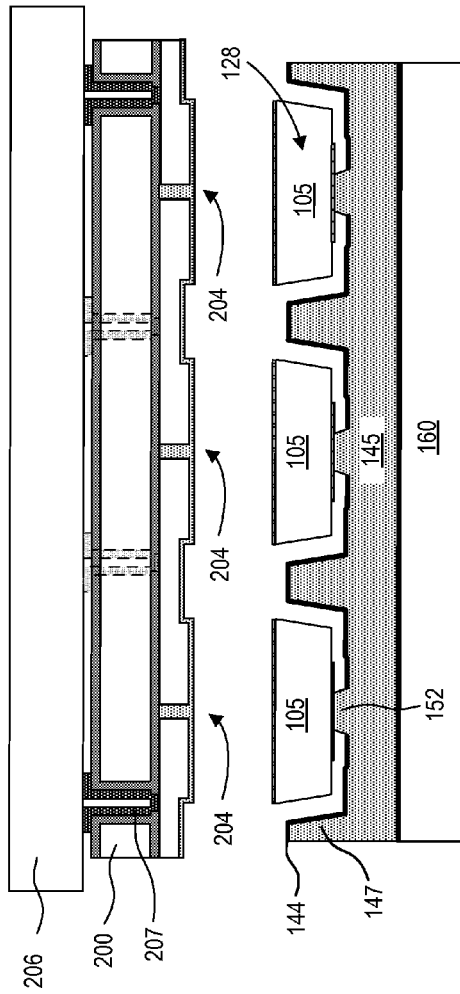


FIG. 11A

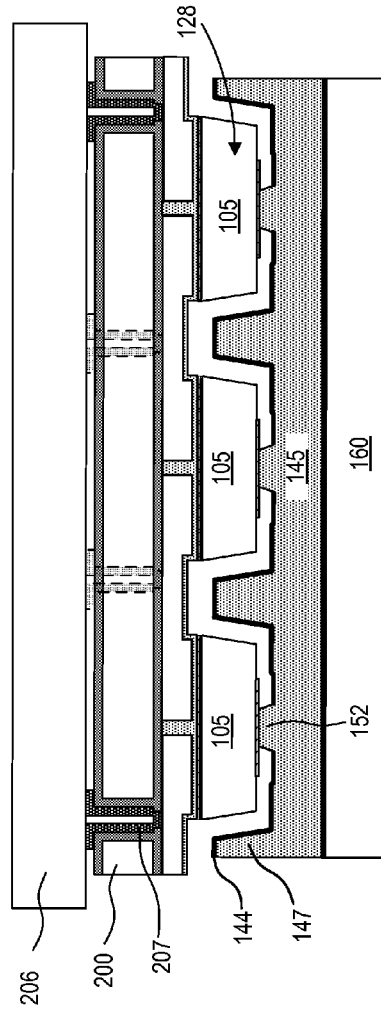


FIG. 11B

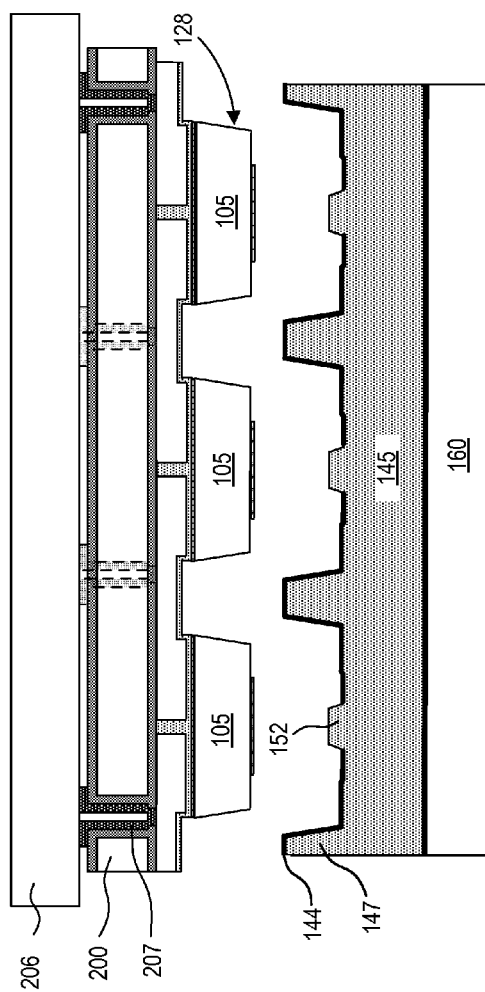


FIG. 11C

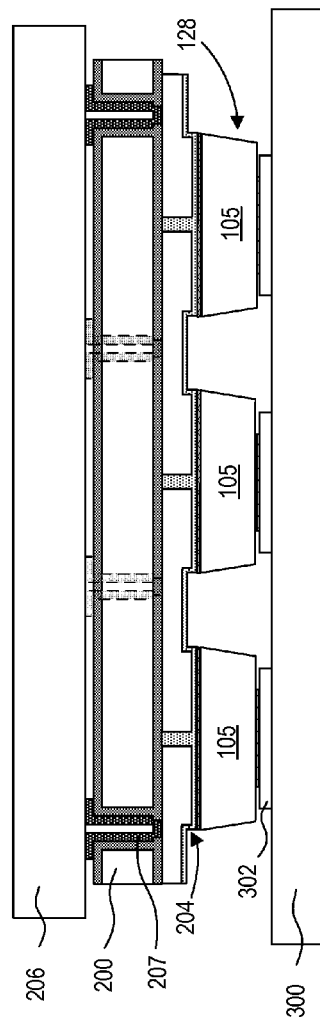


FIG. 11D

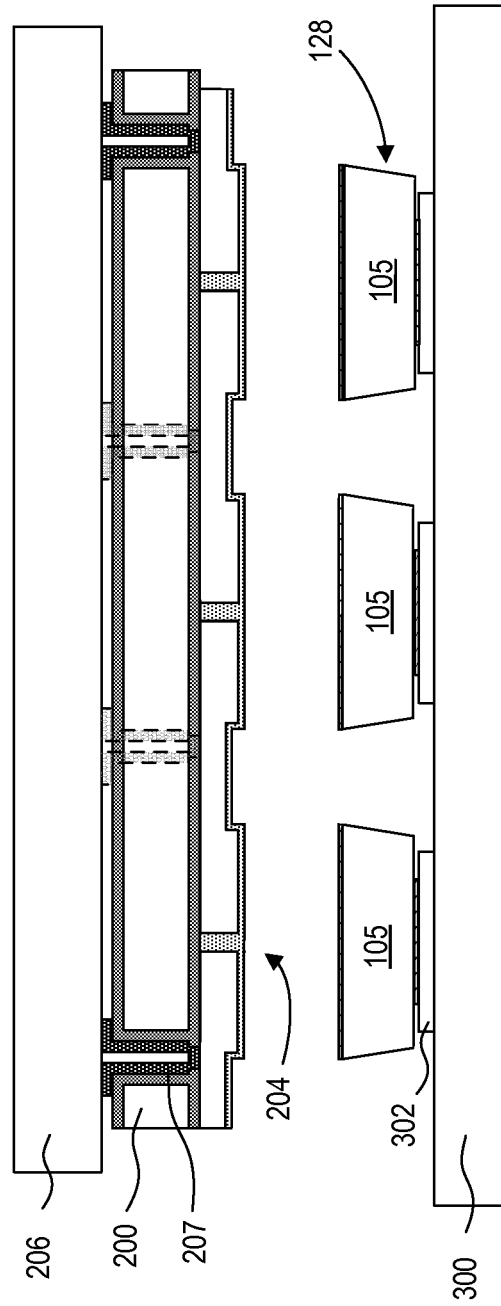


FIG. 11E

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MICRO DEVICE WITH STABILIZATION POST

RELATED APPLICATIONS

This application is a divisional of U.S. patent application Ser. No. 13/937,000, filed Jul. 8, 2013, the full disclosure of which is incorporated herein by reference.

BACKGROUND

1. Field

The present invention relates to micro devices. More particularly embodiments of the present invention relate to the stabilization of micro devices on a carrier substrate.

2. Background Information

Commercial manufacturing and packaging of micro devices often becomes more challenging as the scale of the micro devices decreases. Some examples of micro devices include radio frequency (RF) microelectromechanical systems (MEMS) microswitches, light-emitting diode (LED) display systems, and MEMS or quartz-based oscillators.

One implementation for transferring devices includes peeling devices from an adhesive sheet using a vacuum nozzle that is included in a mounting head. Once the device is picked up by the vacuum pressure, it can be moved by the mounting head to a receiving substrate. A camera may image the receiving substrate to assist the system in placing the device on the receiving substrate. When the mounting head is positioned in the desired location above the receiving substrate, the vacuum pressure can be adjusted to allow the device to stay positioned on the receiving substrate while the mounting head moves away from the receiving substrate.

In another implementation, devices are formed on an adhesive layer that is partially removed using a solvent. This results in only a bridging portion of the adhesive layer connecting the device to a host substrate. To prepare the devices for removal from the substrate, a patterned elastomeric transfer stamp can be selectively applied in order to fracture the bridging portions of the adhesive layer and transfer the devices from the host substrate.

SUMMARY OF THE INVENTION

A structure and method of forming an array of micro devices which are poised for pick up are disclosed. In an embodiment, a structure includes a stabilization layer including an array of stabilization posts, and the stabilization layer is formed of a thermoset material such as epoxy or benzocyclobutene (BCB) which is associated with 10% or less volume shrinkage during curing, or more particularly about 6% or less volume shrinkage during curing. An array of micro devices are on the array of stabilization posts. Each micro device may include a bottom surface that is wider than a corresponding stabilization post directly underneath the bottom surface. An array of bottom conductive contacts may be formed on the bottom surfaces of the array micro devices. An array of top conductive contacts may be formed on top of the array of micro devices. In an embodiment the array of stabilization posts are separated by a pitch of 1 μm to 100 μm , or more specifically 1 μm to 10 μm .

The stabilization layer may be bonded to a carrier substrate. The stabilization layer may have an array of stabilization cavities having stabilization cavity sidewalls surrounding the stabilization posts. An adhesion promoter layer may be formed between the carrier substrate and the stabilization layer to increase adhesion. A sacrificial layer may also be

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located between the stabilization layer and the array of micro devices, where the array of stabilization posts also extend through a thickness of the sacrificial layer. In an embodiment, the sacrificial layer is formed of a material such as an oxide or nitride. An adhesion promoter layer may also be formed between the stabilization layer and the sacrificial layer to increase adhesion, where the array of stabilization posts also extend through a thickness of the adhesion promoter layer. Each stabilization post may be x-y centered below a corresponding micro device or may be off-centered with respect to the corresponding micro devices.

The array of micro devices may be micro LED devices, and may be designed to emit a specific wavelength such as a red, green, or blue light. In an embodiment, each micro LED device includes a device layer formed of a p-doped semiconductor layer, one or more quantum well layers over the p-doped semiconductor layer, and an n-doped semiconductor layer. For example, where the micro LED device is designed to emit a green or blue light, the p-doped layer may comprise GaN and the n-doped layer may also comprise GaN.

One embodiment includes patterning a device layer to form an array of micro device mesa structures over a handle substrate, forming a patterned sacrificial layer including an array of openings over the corresponding array of micro device mesa structures, forming a stabilization layer over the patterned sacrificial layer and within the array of openings, and removing the handle substrate. The stabilization layer may be bonded to a carrier substrate prior to removing the handle substrate. Bonding the stabilization layer to the carrier substrate may include curing. The stabilization layer may be formed of a thermoset material, which may be BCB in one embodiment.

In an embodiment, the array of openings are formed directly over an array of conductive contacts of the corresponding array of micro device mesa structures. In an embodiment, patterning the device layer to form the array of micro device mesa structures leaves unremoved portions of the device layer between the array of micro device mesa structures, and the unremoved portions of the device layer are subsequently removed to form laterally separate micro LED devices. Removing the unremoved portions of the device layer may include thinning the array of micro device mesa structures so that an exposed top surface of the array of micro LED devices is below an exposed top surface of the patterned sacrificial layer between the micro LED devices. The patterned sacrificial layer is removed to form an open space below and around each micro device, in an embodiment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a cross-sectional side view illustration of a bulk LED substrate in accordance with an embodiment of the invention.

FIG. 1B is a cross-sectional side view illustration of a device wafer including circuitry in accordance with an embodiment of the invention.

FIG. 2A is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate in accordance with an embodiment of the invention.

FIG. 2B is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate in accordance with an embodiment of the invention.

FIG. 3 is a cross-sectional side view illustration of a device layer patterned to form an array of micro device mesa structures over a handle substrate in accordance with an embodiment of the invention.

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FIG. 4 is a cross-sectional side view illustration of an adhesion promoter layer and a sacrificial layer including an array of openings formed over an array of micro device mesa structures in accordance with an embodiment of the invention.

FIG. 5 is a cross-sectional side view illustration of a stabilization layer formed over an adhesion promoter layer and a sacrificial layer and within an array of openings included in the sacrificial layer in accordance with an embodiment of the invention.

FIG. 6 is a cross-sectional side view illustration of bringing together a carrier substrate and micro device mesa structures formed on a handle substrate in accordance with an embodiment of the invention.

FIG. 7 is a cross-sectional side view illustration of the removal of a growth substrate in accordance with an embodiment of the invention.

FIG. 8 is a cross-sectional side view illustration of the removal of an epitaxial growth layer and a portion of a device layer in accordance with an embodiment of the invention.

FIGS. 9A-9B are cross-sectional side view illustrations of patterned conductive contacts formed over an array of laterally separate micro devices in accordance with an embodiment of the invention.

FIG. 10A is a cross-sectional side view illustration of an array of micro devices formed on array of stabilization posts after removal of a sacrificial layer in accordance with an embodiment of the invention.

FIGS. 10B-10C are schematic top view illustrations of example stabilization post locations relative to a group of micro devices in accordance with an embodiment of the invention.

FIGS. 11A-11E are cross-sectional side view illustrations of an array of electrostatic transfer heads transferring micro devices from a carrier substrate to a receiving substrate in accordance with an embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

Embodiments of the present invention describe a method and structure for stabilizing an array of micro devices such as micro light emitting diode (LED) devices and micro chips on a carrier substrate so that they are poised for pick up and transfer to a receiving substrate. For example, the receiving substrate may be, but is not limited to, a display substrate, a lighting substrate, a substrate with functional devices such as transistors or integrated circuits (ICs), or a substrate with metal redistribution lines. While embodiments of some of the present invention are described with specific regard to micro LED devices comprising p-n diodes, it is to be appreciated that embodiments of the invention are not so limited and that certain embodiments may also be applicable to other micro semiconductor devices which are designed in such a way so as to perform in a controlled fashion a predetermined electronic function (e.g. diode, transistor, integrated circuit) or photonic function (LED, laser). Other embodiments of the present invention are described with specific regard to micro devices including circuitry. For example, the micro devices may be based on silicon or SOI wafers for logic or memory applications, or based on GaAs wafers for RF communications applications.

In various embodiments, description is made with reference to figures. However, certain embodiments may be practiced without one or more of these specific details, or in combination with other known methods and configurations. In the following description, numerous specific details are set forth, such as specific configurations, dimensions and pro-

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cesses, etc., in order to provide a thorough understanding of the present invention. In other instances, well-known semiconductor processes and manufacturing techniques have not been described in particular detail in order to not unnecessarily obscure the present invention. Reference throughout this specification to "one embodiment," "an embodiment" or the like means that a particular feature, structure, configuration, or characteristic described in connection with the embodiment is included in at least one embodiment of the invention. Thus, the appearances of the phrase "in one embodiment," "an embodiment" or the like in various places throughout this specification are not necessarily referring to the same embodiment of the invention. Furthermore, the particular features, structures, configurations, or characteristics may be combined in any suitable manner in one or more embodiments.

The terms "over", "spanning", "to", "between", and "on" as used herein may refer to a relative position of one layer with respect to other layers. One layer "over", "spanning", or "on" another layer or bonded "to" another layer may be directly in contact with the other layer or may have one or more intervening layers. One layer "between" layers may be directly in contact with the layers or may have one or more intervening layers.

The terms "micro" device, "micro" LED device, or "micro" chip as used herein may refer to the descriptive size of certain devices, devices, or structures in accordance with embodiments of the invention. As used herein the term "micro device" specifically includes "micro LED device" and "micro chip". As used herein, the terms "micro" devices or structures are meant to refer to the scale of 1 to 100 μm . However, it is to be appreciated that embodiments of the present invention are not necessarily so limited, and that certain aspects of the embodiments may be applicable to larger, and possibly smaller size scales. In an embodiment, a single micro device in an array of micro devices, and a single electrostatic transfer head in an array of electrostatic transfer heads both have a maximum dimension, for example length or width, of 1 to 100 μm . In an embodiment, the top contact surface of each micro device or electrostatic transfer head has a maximum dimension of 1 to 100 μm , or more specifically 3 to 20 μm . In an embodiment, a pitch of an array of micro devices, and a corresponding array of electrostatic transfer heads is (1 to 100 μm) by (1 to 100 μm), for example a 20 μm by 20 μm pitch or 5 μm by 5 μm pitch.

In the following embodiments, the mass transfer of an array of pre-fabricated micro devices with an array of transfer heads is described. For example, the pre-fabricated micro devices may have a specific functionality such as, but not limited to, an LED for light-emission, silicon IC for logic and memory, and gallium arsenide (GaAs) circuits for radio frequency (RF) communications. In some embodiments, arrays of micro LED devices which are poised for pick up are described as having a 20 μm by 20 μm pitch, or 5 μm by 5 μm pitch. At these densities, a 6 inch substrate, for example, can accommodate approximately 165 million micro LED devices with a 10 μm by 10 μm pitch, or approximately 660 million micro LED devices with a 5 μm by 5 μm pitch. A transfer tool including an array of transfer heads matching an integer multiple of the pitch of the corresponding array of micro LED devices can be used to pick up and transfer the array of micro LED devices to a receiving substrate. In this manner, it is possible to integrate and assemble micro LED devices into heterogeneously integrated systems, including substrates of any size ranging from micro displays to large area displays, and at high transfer rates. For example, a 1 cm by 1 cm array of micro device transfer heads can pick up and transfer more

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than 100,000 micro devices, with larger arrays of micro device transfer heads being capable of transferring more micro devices.

In one aspect, embodiments of the invention describe a structure for stabilizing an array of micro devices such as micro light emitting diode (LED) devices on a carrier substrate so that they are poised for pick up and transfer to a receiving substrate. In an embodiment, an array of micro devices are held in place on an array of stabilization posts on a carrier substrate. In an embodiment, the stabilization posts are formed of an adhesive bonding material. In this manner, the array of stabilization posts may retain the array of micro devices in place on a carrier substrate while also providing a structure from which the array of micro devices are readily picked up. In an embodiment, the adhesive bonding material includes a thermoset material such as, but not limited to, benzocyclobutene (BCB) or epoxy. In an embodiment, the thermoset material may be associated with 10% or less volume shrinkage during curing, or more particularly about 6% or less volume shrinkage during curing. In this manner low volume shrinkage during curing of the adhesive bonding material may not cause delamination between the array of stabilization posts and the array of micro devices, and may allow for uniform adhesion between the array stabilization posts and the array of micro devices supported by the array of stabilization posts. In one aspect, the adhesive bonding material (e.g. BCB) forms stabilization cavity sidewalls that are advantageously positioned to contain micro device within a stabilization cavity formed by the sidewall. In this respect, even if a micro device loses adherence to a stabilization post, it may still be poised for pick up because it is still positioned within an acceptable tolerance (defined by the stabilization cavity) to be transferred to a receiving substrate.

In one aspect of embodiments of the invention, the array of micro devices are formed in a one sided process sequence in which a device layer is etched to form an array of micro device mesa structures prior to applying a stabilization layer (the stabilization layer having the adhesive bonding material that forms the stabilization posts). A one sided process sequence is distinguishable from a two sided process sequence, which is characterized by etching mesa structures in the device layer after bonding to a stabilization layer. Suitability of a one sided process or two sided process may depend upon the system requirement, and materials being used. For example, where the micro devices are micro LED devices, the devices layers may be formed from different materials selected for different emission spectra. By way of example, a red-emitting micro LED device may be formed of a GaP (5.45 Å lattice constant) based material grown on a GaAs substrate (5.65 Å lattice constant). By way of comparison, a blue-emitting or green-emitting micro LED device may be formed of a GaN (5.18 Å lattice constant) based material grown on a sapphire substrate (4.76 Å lattice constant). It has been observed that when fabricating devices at the "micro" scale in accordance with the embodiments of the invention, that the stored energy in the form of stress in the device layer, typically grown by heterogeneous growth techniques on a lattice-mismatched growth substrate, that stressed device layer may shift upon removal of the growth substrate, potentially causing misalignment between the array of micro devices that are formed over the array of stabilization posts. In accordance with embodiments of the invention, and in particular when lattice mismatch between the device layer and growth substrate is greater than 0.2 Å, a one sided process sequence is performed in order to reduce the amount of shifting between the micro devices and stabilization posts by

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forming micro device mesa structures on stabilization posts prior to removing the growth substrate.

Without being limited to a particular theory, embodiments of the invention utilize transfer heads and head arrays which operate in accordance with principles of electrostatic grippers, using the attraction of opposite charges to pick up micro devices. In accordance with embodiments of the present invention, a pull-in voltage is applied to a transfer head in order to generate a grip pressure on a micro device and pick up the micro device. In accordance with embodiments of the invention, the minimum amount pick up pressure required to pick up a micro device from a stabilization post can be determined by the adhesion strength between the adhesive bonding material from which the stabilization posts are formed and the micro device (or any intermediate layer), as well as the contact area between the top surface of the stabilization post and the micro device. For example, adhesion strength which must be overcome to pick up a micro device is related to the minimum pick up pressure generated by a transfer head as provided in equation (1):

$$P_1 A_1 = P_2 A_2 \quad (1)$$

where P_1 is the minimum grip pressure required to be generated by a transfer head, A_1 is the contact area between a transfer head contact surface and micro device contact surface, A_2 is the contact area on a top surface of a stabilization post, and P_2 is the adhesion strength on the top surface of a stabilization post. In an embodiment, a grip pressure of greater than 1 atmosphere is generated by a transfer head. For example, each transfer head may generate a grip pressure of 2 atmospheres or greater, or even 20 atmospheres or greater without shorting due to dielectric breakdown of the transfer heads. Due to the smaller area, a higher pressure is realized at the top surface of the corresponding stabilization post than the grip pressure generated by a transfer head. In an embodiment, a bonding layer is placed between each micro device and stabilization post in order to aid in bonding each micro device to a receiving substrate. A variety of different bonding layers with different melting temperatures are compatible with embodiments of the invention. For example, heat may or may not be applied to the transfer head assembly, carrier substrate, and/or receiving substrate during the pick up, transfer, and bonding operations. In some embodiments, the bonding layer may be a comparatively higher melting temperature material such as gold. In some embodiments the bonding layer is a comparatively lower melting temperature material such as indium. In some embodiments, the transfer head assembly may be maintained at an elevated temperature during the pick up and transfer operations in order to assist bonding to the receiving substrate without thermal cycling of the transfer head assembly. In one embodiment, the bonding layer is gold, and the bonding layer is not liquefied during the pick up or transfer operations. In one embodiment the bonding layer is indium, and the bonding layer is liquefied during the pick up and transfer operations. In such an embodiment, the bonding layer may be partially picked up and transferred to the receiving substrate.

In another embodiment, the bonding layer is formed of a material characterized by a low tensile strength. For example, indium is characterized by a tensile strength of approximately 4 MPa which can be less than or near the adhesion strength between a gold/BCB bonding interface of 10 MPa or less, and which is significantly lower than an exemplary 30 MPa adhesion strength between a gold/BCB bonding interface (determined with stud pull test) when treated with adhesion promoter AP3000, an organosilane compound in 1-methoxy-2-propanol available from The Dow Chemical Company. In an

embodiment, the bonding layer is cleaved during the pick up operation due to the lower tensile strength, and a phase change is not created during the pick up operation. Though, a phase change may still be created in the portion of the bonding layer which is picked up with the micro device during placement of the micro device onto a receiving substrate to aid in bonding of the micro device to the receiving substrate.

In another aspect, embodiments of the invention describe a manner of forming an array of micro devices which are poised for pick up in which conductive contact layers can be formed on top and bottom surfaces of the micro devices, and annealed to provide ohmic contacts. Where a conductive contact is formed on a top surface of a micro device, the stabilization layer is formed of a material which is capable of withstanding the associated deposition and annealing temperatures. For example, a conductive contact may require annealing at temperatures between 200° C. to 350° C. to form an ohmic contact with the micro device. In this manner, embodiments of the invention may be utilized to form arrays of micro LED devices based upon a variety of different semiconductor compositions for emitting various different visible wavelengths. For example, micro LED growth substrates including active devices layers formed of different materials for emitting different wavelengths (e.g. red, green, and blue wavelengths) can all be processed within the general sequence of operations of the embodiments.

In the following description exemplary processing sequences are described for forming an array of micro devices on an array of stabilization posts. Specifically, exemplary processing sequences are described for forming an array of micro LED devices and an array of micro chips. Where possible, similar features are illustrated with similar annotations in the figures and following description.

FIG. 1A is an example cross-sectional side view illustration of a bulk LED substrate **100** in accordance with an embodiment of the invention. In the illustrated embodiment, bulk LED substrate **100** includes a growth substrate **102**, an epitaxial growth layer **103**, and a device layer **105**. In an embodiment, growth substrate **102** is sapphire and may be approximately 500 μm thick. Using a sapphire growth substrate may correspond with manufacturing blue emitting LED devices (e.g. 450-495 nm wavelength) or green emitting LED devices (e.g. 495-570 nm wavelength). It is to be appreciated, that while the specific embodiments illustrated and described in the following description may be directed to formation of green or blue emitting LED devices, the following sequences and descriptions are also applicable to the formation of LED devices that emit wavelengths other than blue and green. Epitaxial growth layer **103** may be grown on growth substrate **102** using known epitaxial growth techniques. Epitaxial growth layer **103** may be grown on growth substrate **102** at a relatively high temperature to facilitate gliding out dislocations in the layer. In an embodiment, epitaxial growth layer **103** is a gallium nitride (GaN) based material.

Device layer **105** may be formed on epitaxial growth layer **103**, as shown in FIG. 1A. In an embodiment the growth substrate **102** is a sapphire substrate and is approximately 200 μm thick. The epitaxial growth layer **103** may be any suitable thickness such as between 300 Å-5 μm . In the illustrated embodiment, device layer **105** includes layers for forming LED devices. In FIG. 1A, a zoomed-in view of an example device layer **105** illustrates one or more quantum well layers **110** between doped semiconductor layer **108** (e.g. n-doped) and doped semiconductor layer **112** (e.g. p-doped), although the doping of layers **108**, **112** may be reversed. In an embodiment, doped semiconductor layer **108** is formed of GaN and is approximately 0.1 μm to 3 μm thick. The one or more

quantum well layers **110** may have a thickness of approximately 0.5 μm . In an embodiment, doped semiconductor layer **112** is formed of GaN, and is approximately 0.1 μm to 2 μm thick.

FIG. 1B is a cross-sectional side view illustration of a device wafer including circuitry in accordance with an embodiment of the invention. In accordance with embodiments of the invention, the device wafer **180** may be formed of a variety of materials depending upon the desired function. For example, in an embodiment, the device wafer **180** is a silicon wafer, or silicon-on-insulator (SOI) wafer for logic or memory. In an embodiment, the device wafer **180** is a gallium arsenide (GaAs) wafer for radio frequency (RF) communications. These are merely examples, and embodiments of the invention envision are not limited to silicon or GaAs wafers, nor are embodiments limited to logic, memory, or RF communications.

In an embodiment, the device wafer **180** includes an active device layer **185**, optional buried oxide layer **184**, and base substrate **182**. In the interest of clarity, the following description is made with regard to an SOI device wafer **180**, including an active device layer **185**, buried oxide layer **184**, and base silicon substrate **182**, though other types of devices wafers may be used, including bulk semiconductor wafers. In an embodiment, the active device layer **185** may include working circuitry to control one or more LED devices. In some embodiments, back-end processing may be performed within the active device layer **185**. Accordingly, in an embodiment, the active device layer **185** includes an active silicon layer **187** including a device such as a transistor, metal build-up layers **188** including interconnects **189**, bonding pads **190**, and passivation **192**.

In interests of clarity the remainder of the description is made with regard to the bulk LED substrate of FIG. 1A. However, it is appreciated that the process sequences in the following description may be used to fabricate other micro devices. For example, micro chips may be similarly manufactured by substituting bulk LED substrate **100** with device wafer **180** and using the same or similar processes as described with reference to bulk LED substrate **100**. Accordingly, in the following description, both the growth substrate **102** and base substrate **182** can alternatively be referred to more generically as a "handle" substrate so as to not preclude the processing sequence on a growth substrate **102** from being applied to the a processing sequence on a base substrate **182**.

FIG. 2A is a cross-sectional side view illustration of a patterned conductive contact layer on bulk LED substrate **100** in accordance with an embodiment of the invention. A conductive contact layer may be formed over device layer **105** using a suitable technique such as sputtering or electron beam physical deposition followed by etching or liftoff to form the array of conductive contacts **120**. In an embodiment, the array of conductive contacts **120** have a thickness of approximately 0.1 μm -2 μm , and may include a plurality of different layers. For example, a conductive contact **120** may include an electrode layer **121** for ohmic contact, a mirror layer **122**, an adhesion/barrier layer **123**, a diffusion barrier layer **124**, and a bonding layer **125**. In an embodiment, electrode layer **121** may make ohmic contact to a p-doped semiconductor layer **112**, and may be formed of a high work-function metal such as nickel. In an embodiment, a mirror layer **122** such as silver is formed over the electrode layer **121** to reflect the transmission of the visible wavelength. In an embodiment, titanium is used as an adhesion/barrier layer **123**, and platinum is used as a diffusion barrier **124** to bonding layer **125**. Bonding layer **125** may be formed of a variety of materials which can be chosen for bonding to the receiving substrate and/or to

achieve the requisite tensile strength or adhesion or surface tension with the stabilization posts. Following the formation of layers **121-125**, the substrate stack can be annealed to form an ohmic contact. For example, a p-side ohmic contact may be formed by annealing the substrate stack at 510° C. for 10 minutes.

In an embodiment, bonding layer **125** is formed of a conductive material (both pure metals and alloys) which can diffuse with a metal forming a contact pad on a receiving substrate (e.g. gold, indium, or tin contact pad) and has a liquidus temperature above 200° C. such as tin (231.9° C.) or bismuth (271.4° C.), or a liquidus temperature above 300° C. such as gold (1064° C.) or silver (962° C.). In some embodiments, bonding layer **125** such as gold may be selected for its poor adhesion with the adhesive bonding material used to form the stabilization posts. For example, noble metals such as gold are known to achieve poor adhesion with BCB. In this manner, sufficient adhesion is created to maintain the array of micro LED devices on the stabilization posts during processing and handling, as well as to maintain adjacent micro LED devices in place when another micro LED device is being picked up, yet also not create too much adhesion so that pick up can be achieved with an applied pick up pressure on the transfer head of 20 atmospheres or less, or more particularly 5-10 atmospheres.

In the embodiment illustrated in FIG. 2A, where bonding layer **125** has a liquidus temperature above the annealing temperature for forming the p-side ohmic contact, the anneal (e.g. 510° C. for 10 minutes) can be performed after the formation of the patterned conductive contact layer **120**, including bonding layer **125**. Where bonding layer **125** has a liquidus temperature below the annealing temperature for forming the p-side ohmic contact, the bonding layer **125** may be formed after annealing.

FIG. 2B is a cross-sectional side view illustration of a patterned conductive contact layer on a bulk LED substrate **100** in accordance with an embodiment of the invention. The embodiment illustrated in FIG. 2B may be particularly useful where bonding layer **125** is formed of a material with a liquidus temperature below the annealing temperature of the p-side ohmic contact, though the embodiment illustrated in FIG. 2B is not limited to such and may be used where the bonding layer **125** is formed of a material with a liquidus temperature above the annealing temperature of the p-side ohmic contact. In such embodiments, electrode layer **121** and mirror layer **122** may be formed similarly as described with regard to FIG. 2A. Likewise, adhesion/barrier layer **123** and diffusion barrier **124** may be formed similarly as described with regard to FIG. 2A with one difference being that the layers **123**, **124** may optionally wrap around the sidewalls of the layers **121**, **122**. Following the formation of layers **121-124**, the substrate stack can be annealed to form an ohmic contact. For example, a p-side ohmic contact may be formed by annealing the substrate stack at 510° C. for 10 minutes. After annealing layer **121-124** to form the p-side ohmic contact, the bonding layer **125** may be formed. In an embodiment, the bonding layer **125** has a smaller width than for layers **121-124**.

In an embodiment, bonding layer **125** has a liquidus temperature or melting temperature of approximately 350° C. or lower, or more specifically of approximately 200° C. or lower. At such temperatures the bonding layer may undergo a phase change without substantially affecting the other components of the micro LED device. In an embodiment, the resultant bonding layer may be electrically conductive. In accordance with some embodiments, the bonding layer **125** may be a solder material, such as an indium, bismuth, or tin based

solder, including pure metals and metal alloys. In a particular embodiment, the bonding layer **125** is indium.

FIG. 3 is a cross-sectional side view illustration of device layer **105** patterned to form an array of micro device mesa structures **127** over a handle substrate that includes growth substrate **102** and epitaxial growth layer **103** in accordance with an embodiment of the invention. Etching of layers **108**, **110**, and **112** of device layer **105** may be accomplished using suitable etch chemistries for the particular materials. For example, n-doped semiconductor layer **108**, quantum well layer(s) **110**, and p-doped layer **112** may be dry etched in one operation with a BCl₃ and Cl₂ chemistry. As FIG. 3 illustrates, device layer **105** may not be etched completely through which leaves unremoved portions **129** of device layer **105** that connect the micro device mesa structures **127**. In one example, the etching of device layer **105** is stopped in n-doped semiconductor layer **108** (which may be n-doped GaN). Height of the micro device mesa structures **127** (not including the thickness of the unremoved portions **129**) may correspond substantially to the height of the laterally separate micro devices to be formed. In accordance with embodiments of the invention, the device layer **105** may alternatively be completely etched through. For example, where the bulk LED substrate **100** is replaced with a device wafer **180** in the processing sequence, etching may stop on the buried oxide layer **184**.

FIG. 4 is a cross-sectional side view illustration of an adhesion promoter layer **144** and a sacrificial layer **135** including an array of openings **133** formed over the array of micro device mesa structures **127** in accordance with an embodiment of the invention. In an embodiment, sacrificial layer **135** is between approximately 0.5 and 2 microns thick. In an embodiment, sacrificial layer **135** is formed of an oxide (e.g. SiO₂) or nitride (e.g. SiN_x), though other materials may be used which can be selectively removed with respect to the other layers. In an embodiment, sacrificial layer **135** is deposited by sputtering, low temperature plasma enhanced chemical vapor deposition (PECVD), or electron beam evaporation to create a low quality layer, which may be more easily removed than a higher quality layer deposited by other methods such as atomic layer deposition (ALD) or high temperature PECVD.

Still referring to FIG. 4, after the formation of sacrificial layer **135**, an adhesion promoter layer **144** may optionally be formed in order to increase adhesion of the stabilization layer **145** (not yet formed) to the sacrificial layer **135**. A thickness of 100-300 angstroms may be sufficient to increase adhesion.

Specific metals that have good adhesion to both the sacrificial layer **135** and a BCB stabilization layer (not yet formed) include, but are not limited to, titanium and chromium. For example, sputtered or evaporated titanium or chromium can achieve an adhesion strength (stud pull) of greater than 40 MPa with BCB.

After forming sacrificial layer **135**, the sacrificial layer **135** is patterned to form an array of openings **133** over the array of conductive contacts **120**. If adhesion layer **144** is present, it can also be patterned to form the array of openings **133**, exposing the array of conductive contacts **120** as illustrated in FIG. 4. In an example embodiment, a fluorinated chemistry (e.g. HF vapor, or CF₄ or SF₆ plasma) is used to etch the SiO₂ or SiN_x sacrificial layer **135**.

As will become more apparent in the following description the height, and length and width of the openings **133** in the sacrificial layer **135** correspond to the height, and length and width (area) of the stabilization posts to be formed, and resultantly the adhesion strength that must be overcome to pick up the array of micro devices (e.g. micro LED devices) poised for pick up on the array of stabilization posts. In an embodi-

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ment, openings 133 are formed using lithographic techniques and have a length and width of approximately 1 μm by 1 μm , though the openings may be larger or smaller so long as the openings have a width (or area) that is less than the width (or area) of the conductive contacts 120 and/or micro LED devices. Furthermore, the height, length and width of the openings 131 between the sacrificial layer 135 formed along sidewalls between the micro device mesa structures 127 will correspond to the height, length and width of the stabilization cavity sidewalls to be formed. Accordingly, increasing the thickness of the sacrificial layer 135 and space separating adjacent micro device mesa structures 127 will have the effect of decreasing the size of the stabilization cavity sidewalls.

FIG. 5 is a cross-sectional side view illustration of a stabilization layer 145 formed over adhesion promoter layer 144 and sacrificial layer 135 and within an array of openings 133 included in sacrificial layer 135 in accordance with an embodiment of the invention. Stabilization layer 145 may be formed of an adhesive bonding material. The adhesive bonding material may be a thermosetting material such as benzocyclobutene (BCB) or epoxy. In an embodiment, the thermosetting material may be associated with 10% or less volume shrinkage during curing, or more particularly about 6% or less volume shrinkage during curing so as to not delaminate from the conductive contacts 120 on the micro device mesa structures 127. In order to increase adhesion to the underlying structure, in addition to, or in alternative to adhesion promoter layer 144, the underlying structure can be treated with an adhesion promoter such as AP3000, available from The Dow Chemical Company, in the case of a BCB stabilization layer in order to condition the underlying structure. AP3000, for example, can be spin coated onto the underlying structure, and soft-baked (e.g. 100° C.) or spun dry to remove the solvents prior to applying the stabilization layer 145 over the patterned sacrificial layer 135.

In an embodiment, stabilization layer 145 is spin coated or spray coated over the patterned sacrificial layer 135, though other application techniques may be used. Following application of the stabilization layer 145, the stabilization may be pre-baked to remove solvents, resulting in a b-staged layer. In an embodiment, the stabilization layer 145 is thicker than the height of openings 131, when present, between micro device mesa structures 127, and openings 133 in the patterned sacrificial layer 135. In this manner, the thickness of the stabilization layer filling openings 133 will become stabilization posts 152, the thickness of the stabilization layer filling openings 131 will become stabilization cavity sidewalls 147, and the remainder of the thickness of the stabilization layer 145 over the filled openings 131, 133 can function to adhesively bond the bulk LED substrate 100 to a carrier substrate.

FIG. 6 is a cross-sectional side view illustration of bringing together (bonding) a carrier substrate 160 and micro device mesa structures 127 formed on the handle substrate in accordance with an embodiment of the invention. In order to increase adhesion with the stabilization layer 145, an adhesion promoter layer 162 can be applied to the carrier substrate 160 prior to bonding the bulk LED substrate 100 to the carrier substrate 160 similarly as described above with regard to adhesion promoter layer 144. Likewise, in addition to, or in alternative to adhesion promoter layer 162, an adhesion promoter such as AP3000 may be applied to the surface of the carrier substrate 160 or adhesion promoter layer 162. Carrier substrate 160 may be silicon, for example.

Alternatively stabilization layer 145 can be formed on carrier substrate 160 prior to bonding the carrier substrate 160 to the handle substrate. For example, the structure including the patterned sacrificial layer 135 and micro device mesa struc-

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tures 127 can be embossed into an a-staged or b-staged stabilization layer 145 formed on the carrier substrate 160.

Depending upon the particular material of stabilization layer 145, stabilization layer 145 may be thermally cured, or cured with application of UV energy. In an embodiment, stabilization layer 145 is a-staged or b-staged prior to bonding the carrier substrate to the handle substrate, and is cured at a temperature or temperature profile ranging between 150° C. and 300° C. Where stabilization layer 145 is formed of BCB, curing temperatures should not exceed approximately 350° C., which represents the temperature at which BCB begins to degrade. In accordance with embodiments including a bonding layer 125 material characterized by a liquidus temperature (e.g. gold, silver, bismuth) greater than 250° C., full-curing of a BCB stabilization layer 145 can be achieved in approximately 1 hour or less at a curing temperature between 250° C. and 300° C. Other bonding layer 125 materials such as Sn (231.9° C.) may require between 10-100 hours to fully cure at temperatures between 200° C. and the 231.9° C. liquidus temperature. In accordance with embodiments including a bonding layer 125 material characterized by a liquidus temperature below 200° C. (e.g. indium), a BCB stabilization layer 145 may only be partially cured (e.g. 70% or greater). In such an embodiment the BCB stabilization layer 145 may be cured at a temperature between 150° C. and the liquidus temperature of the bonding layer (e.g. 156.7° C. for indium) for approximately 100 hours to achieve at least a 70% cure.

Achieving a 100% full cure of the stabilization layer is not required in accordance with embodiments of the invention. More specifically, the stabilization layer 145 may be cured to a sufficient curing percentage (e.g. 70% or greater for BCB) at which point the stabilization layer 145 will no longer reflow. Moreover, it has been observed that such partially cured (e.g. 70% or greater) BCB stabilization layer 145 may possess sufficient adhesion strengths with the carrier substrate 160 and patterned sacrificial layer 135 (or any intermediate layer (s)).

FIG. 7 is a cross-sectional side view illustration of the removal of growth substrate 102 in accordance with an embodiment of the invention. When growth substrate 102 is sapphire, laser lift off (LLO) may be used to remove the sapphire. Removal may be accomplished by other techniques such as grinding and etching, depending upon the material selection of the growth substrate 102.

FIG. 8 is a cross-sectional side view illustration of the removal of epitaxial growth layer 103 and a portion of device layer 105 in accordance with an embodiment of the invention. The removal of epitaxial growth layer 103 and a portion of device layer 105 may be accomplished using one or more of Chemical-Mechanical-Polishing (CMP), dry polishing, or dry etch. FIG. 8 illustrates that that unremoved portions 129 of device layer 105 that connected the micro device mesa structures 127 (FIG. 7) are removed in FIG. 8, which leaves laterally separated micro devices 128. In an embodiment, removing unremoved portions 129 of device layer 105 includes thinning the array of micro device mesa structures 127 so that an exposed top surface 109 of each of the laterally separate micro devices 128 are below an exposed top surface 139 of patterned sacrificial layer 135.

In embodiments where the bulk LED substrate 100 includes epitaxial growth layer 103, a portion of the doped semiconductor layer 108 adjacent the epitaxial growth layer may also function as a "buffer". For example, epitaxial growth layer 103 may or may not be doped, while semiconductor layer 108 is n-doped. It may be preferred to remove the epitaxial growth layer 103 using any suitable technique such

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as wet or dry etching, or chemical mechanical polishing (CMP), followed by a timed etch of the remainder of the doped semiconductor layer 108 resulting in the structure illustrated in FIG. 8. In this manner, the thickness of the laterally separate micro devices 128 is largely determined by the etching operation illustrated in FIG. 3 for the formation of the micro device mesa structures 127, combined with the timed etch or etch stop detection of the etching operation illustrated in FIG. 8.

FIGS. 9A-9B are cross-sectional side view illustrations of a patterned conductive contacts 175 formed over an array of laterally separated micro device 128 in accordance with an embodiment of the invention. FIGS. 9A and 9B are substantially similar, with a difference being the arrangement of layers within conductive contacts 120. FIG. 9A corresponds with the conductive contacts 120 illustrated in FIG. 2A while FIG. 9B corresponds with the conductive contacts 120 illustrated in FIG. 2B.

To form conductive contacts 175, a conductive contact layer is formed over micro devices 128 and sacrificial layer 135. The conductive contact layer may be formed of a variety of conductive materials including metals, conductive oxides, and conductive polymers. In an embodiment, conductive contacts are formed of a metal or metal alloy. In an embodiment, the conductive contact layer is formed using a suitable technique such as sputtering or electron beam physical deposition. For example, the conductive contact layer may include BeAu metal alloy, or a metal stack of Au/GeAuNi/Au layers. The conductive contact layer can also be a combination of one or more metal layers and a conductive oxide. In an embodiment, after forming the conductive contact layer, the substrate stack is annealed to generate an ohmic contact between the conductive contact layer and the device layer of micro devices 128. Where the stabilization layer is formed of BCB, the annealing temperature may be below approximately 350° C., at which point BCB degrades. In an embodiment, annealing is performed between 200° C. and 350° C., or more particularly at approximately 320° C. for approximately 10 minutes. After the conductive contact layer is deposited, it can be patterned and etched to form conductive contacts 175, which may be n-metal conductive contacts.

The resultant structures illustrated in FIGS. 9A and 9B are robust enough for handling and cleaning operations to prepare the substrate structure for subsequent sacrificial layer removal and electrostatic pick up. In an exemplary embodiment where the array of micro devices have a pitch of 5 microns, each micro device may have a minimum width (e.g. along the top surface 109) of 4.5 μm , and a separation between adjacent micro devices of 0.5 μm . It is to be appreciated that a pitch of 5 microns is exemplary, and that embodiments of the invention encompass any pitch of 1 to 100 μm as well as larger, and possibly smaller pitches.

FIGS. 9A and 9B illustrate a structure having a stabilization layer 145 that includes an array of stabilization cavities and an array of stabilization posts 152. Each stabilization cavity in the array includes sidewalls 147 (which may be coated with adhesion promoter layer 144) of stabilization layer 145 that surround stabilization posts 152. In FIGS. 9A and 9B, the bottom surface 107 (having dimension D1) of each micro device 128 is wider than the corresponding stabilization post 152 that is directly under the micro device 128. In FIGS. 9A and 9B, sacrificial layer 135 spans along side surfaces 106 of micro devices 128. In the illustrated embodiments, stabilization posts 152 extend through a thickness of sacrificial layer 135 and the stabilization cavity sidewalls 147 of the stabilization layer 145 are taller than the stabilization posts 152. However, in some embodiments, stabilization

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posts 152 are taller than the stabilization cavity sidewalls 147. For example, the thickness of the sacrificial layer 135 and space between laterally adjacent micro devices 128 may affect the size of the stabilization cavity sidewalls 147.

FIG. 10A is a cross-sectional side view illustration of an array of micro devices 128 formed on array of stabilization posts 152 after removal of sacrificial layer 135 in accordance with an embodiment of the invention. In the embodiments illustrated, sacrificial layer 135 is removed resulting in an open space 177 between each micro device 128 and stabilization layer 145. As illustrated, open space 177 includes the open space below each micro device 128 and stabilization layer 145 as well as the open space between each micro device 128 and stabilization cavity sidewalls 147 of stabilization layer 145. A suitable etching chemistry such as HF vapor, CF_4 , or SF_6 plasma may be used to etch the SiO_2 or SiN_x of sacrificial layer 135.

After sacrificial layer 135 is removed, the array of micro devices 128 are on the array of stabilization posts 152 are supported only by the array of stabilization posts 152. At this point, the array of micro devices 128 are poised for pick up transferring to a target or receiving substrate. After sacrificial layer 135 is removed leaving only stabilization posts 152 to support micro devices 128, it is possible that a micro device 128 may shift off of its corresponding stabilization post 152. However, in the illustrated embodiment, the stabilization cavity sidewalls 147 may be advantageously positioned to contain the shifted micro device 128 within the stabilization cavity. Therefore, even when a micro device 128 loses adherence to a stabilization post 152, it may still be poised for pick up because it is still positioned within an acceptable tolerance (defined by the stabilization cavity) to be transferred to a receiving substrate.

To further illustrate, FIGS. 10B-10C are schematic top view illustrations of example stabilization post 152 locations relative to a group of micro devices 128 in accordance with an embodiment of the invention. The cross-sectional side view of FIG. 10A is illustrated along line A-A in FIGS. 10B and 10C. FIG. 10B shows an embodiment where stabilization posts 152 are centered in the x-y directions relative to a top view illustration of micro devices 128. FIG. 10B also shows how stabilization cavity sidewalls 147 can function to contain micro devices 128, if a micro device 128 loses adhesion to a stabilization post 152. FIG. 10C is substantially similar to FIG. 10B except that stabilization posts 153 have replaced stabilization posts 152. Stabilization posts 153 differ from stabilization posts 152 in that they are not centered in the x-y direction relative to a top view illustration of the micro devices 128. Of course, positions of stabilization posts other than the illustrated positions of stabilization posts 152 and 153 are possible. In an embodiment, during the pick up operation described below the off-centered stabilization posts 153 may provide for the creation of a moment when the array of transfer heads contact the array of micro devices in which the micro devices tilt slightly as a result of the applied downward pressure from the array of transfer heads. This slight tilting may aid in overcoming the adhesion strength between the stabilization posts 153 and the array of micro devices 128. Furthermore, such assistance in overcoming the adhesion strength may potentially allow for picking up the array of micro devices with a lower grip pressure. Consequently, this may allow for operation of the array of transfer heads at a lower voltage, and impose less stringent dielectric strength requirements in the dielectric layer covering each transfer head required to achieve the electrostatic grip pressure.

FIGS. 11A-11E are cross-sectional side view illustrations of an array of electrostatic transfer heads 204 transferring

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micro devices **128** from a carrier substrate **160** to a receiving substrate **300** in accordance with an embodiment of the invention. FIG. **11A** is a cross-sectional side view illustration of an array of micro device transfer heads **204** supported by substrate **200** and positioned over an array of micro devices **128** stabilized on stabilization posts **152** of stabilization layer **145** on carrier substrate **160**. The array of micro devices **128** are then contacted with the array of transfer heads **204** as illustrated in FIG. **11B**. As illustrated, the pitch of the array of transfer heads **204** is an integer multiple of the pitch of the array of micro devices **128**. A voltage is applied to the array of transfer heads **204**. The voltage may be applied from the working circuitry within a transfer head assembly **206** in electrical connection with the array of transfer heads through vias **207**. The array of micro devices **128** is then picked up with the array of transfer heads **204** as illustrated in FIG. **11C**. The array of micro devices **128** is then placed in contact with contact pads **302** (e.g. gold, indium, or tin) on a receiving substrate **300**, as illustrated in FIG. **11D**. The array of micro devices **128** is then released onto contact pads **302** on receiving substrate **300** as illustrated in FIG. **11E**. For example, the receiving substrate may be, but is not limited to, a display substrate, a lighting substrate, a substrate with functional devices such as transistors or ICs, or a substrate with metal redistribution lines.

In accordance with embodiments of the invention heat may be applied to the carrier substrate, transfer head assembly, or receiving substrate during the pickup, transfer, and bonding operations. For example, heat can be applied through the transfer head assembly during the pick up and transfer operations, in which the heat may or may not liquefy the micro device bonding layers **125**. The transfer head assembly may additionally apply heat during the bonding operation on the receiving substrate that may or may not liquefy one of the bonding layers on the micro device or receiving substrate to cause diffusion between the bonding layers.

The operation of applying the voltage to create a grip pressure on the array of micro devices can be performed in various orders. For example, the voltage can be applied prior to contacting the array of micro devices with the array of transfer heads, while contacting the micro devices with the array of transfer heads, or after contacting the micro devices with the array of transfer heads. The voltage may also be applied prior to, while, or after applying heat to the bonding layers.

Where the transfer heads **204** include bipolar electrodes, an alternating voltage may be applied across a pair of electrodes in each transfer head **204** so that at a particular point in time when a negative voltage is applied to one electrode, a positive voltage is applied to the other electrode in the pair, and vice versa to create the pickup pressure. Releasing the array of micro devices from the transfer heads **204** may be accomplished with a varied of methods including turning off the voltage sources, lower the voltage across the pair of silicon electrodes, changing a waveform of the AC voltage, and grounding the voltage sources.

Furthermore, the method of pickup up and transferring the array of micro devices from a carrier substrate to a receiving substrate described with regard to FIGS. **11A-11E** is appli-

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cable contexts where the micro devices are micro LEDs or other examples of micro devices described herein.

In utilizing the various aspects of this invention, it would become apparent to one skilled in the art that combinations or variations of the above embodiments are possible for stabilizing an array of micro devices on a carrier substrate, and for transferring the array of micro devices. Although the present invention has been described in language specific to structural features and/or methodological acts, it is to be understood that the invention defined in the appended claims is not necessarily limited to the specific features or acts described. The specific features and acts disclosed are instead to be understood as particularly graceful implementations of the claimed invention useful for illustrating the present invention.

What is claimed is:

1. A method of forming an array of micro devices comprising:

patterning a device layer to form an array of micro device mesa structures over a handle substrate;

forming a patterned sacrificial layer including an array of openings over the corresponding array of micro device mesa structures;

forming a stabilization layer over the patterned sacrificial layer and within the array of openings; and

removing the handle substrate.

2. The method of claim 1, wherein each micro device mesa structure includes a p-doped layer, an n-doped layer, and a quantum well layer between the p-doped layer and the n-doped layer.

3. The method of claim 2, further comprising:

forming the array of openings in the patterned sacrificial layer directly over an array of conductive contacts of the corresponding array of micro device mesa structures.

4. The method of claim 2, wherein the patterning the device layer to form the array of micro device mesa structures leaves unremoved portions of the device layer between the array of micro device mesa structures, and further comprising removing the unremoved portions of the device layer to form an array of laterally separate micro LED devices after removing the handle substrate.

5. The method of claim 4, wherein removing the unremoved portions of the device layer comprises thinning the array of micro device mesa structures so that an exposed top surface of the array of micro LED devices is below an exposed top surface of the patterned sacrificial layer between the micro LED devices.

6. The method of claim 1, further comprising bonding the stabilization layer to a carrier substrate prior to removing the handle substrate.

7. The method of claim 6, wherein bonding the stabilization layer to the carrier substrate comprises curing the stabilization layer.

8. The method of claim 1, further comprising removing the patterned sacrificial layer after removing the handle substrate.

9. The method of claim 1, wherein the stabilization layer is formed of a thermoset material.

10. The method of claim 1, wherein the array of openings are separated by a pitch of 1 μm to 10 μm .

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